ERDC TN-EMRRP-EBA-19
June 2013

Metric Selection for Ecosystem Restoration

by Matteo Convertino, Kelsie Baker, Connie Lu, John T. Vogel, Kyle McKay, and Igor Linkov

SUMMARY: This technical note is designed to help ecosystem restoration planners and project managers identify the best metrics to evaluate and select the recommended restoration plan, monitor and assess progress toward achieving project objectives, and, if necessary, inform adaptive management decisions. Performance metrics, or measurable system components used to estimate and track the state of critical aspects of the project, are often the basis for project decision making and furthering scientific understanding. As such, ecosystem restoration planners should take time to carefully select an appropriate and effective metric set. To help planners with this task, this technical note accomplishes the following:

1. Reviews current USACE ecosystem restoration planning and monitoring policy, regulations and guidelines.
2. Explains the importance of metric selection and its roles during planning and post-construction monitoring and assessment.
3. Reviews common options for identifying and selecting metrics including conceptual modeling, historical precedence, and best professional judgment.
4. Presents two metric evaluation methods, screening and multi-criteria decision analysis.
5. Discusses metric application to ecosystem restoration project planning and monitoring.

This technical note is expected to assist ecosystem restoration practitioners in selecting and applying metrics that can be used to further scientific understanding, resolve hypotheses, and evaluate expected and/or realized project impacts.

BACKGROUND: Environmental protection has been a primary mission of the US Army Corps of Engineers (USACE) since the passing of Public Law 101-640 in November of 1990. Since then, a substantial number of USACE offices have been involved in the planning, design, and construction of water-related restoration projects with a focus on wetlands, submerged aquatic vegetation, oyster reefs, riparian forest, and wet prairie (Miner 2005). The objective of these Corps ecosystem restoration projects is to increase the net quantity and/or quality of desired ecosystem resources by restoring degraded ecosystem function, structure, and processes (Engineer Regulation (ER) 1105-2-100 (USACE 2000)). Planning an ecosystem restoration project includes identifying problems and opportunities, inventorying and forecasting conditions, and formulating and evaluating alternative plans. Plans are evaluated based on an objective characterization of the plan's inputs and outputs (i.e., what conditions are produced by a project, as opposed to how does the presence of the project alter conditions that might have otherwise existed). The results of the evaluations are then compared against one another. These planning steps require metrics that indicate the state of the ecosystem and clearly identify quantifiable ecosystem restoration outputs

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 2013**	2. REPORT TYPE	3. DATES COVERED **00-00-2013 to 00-00-2013**
4. TITLE AND SUBTITLE **Metric Selection for Ecosystem Restoration**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **US Army Engineer Research and Development Center,Ecosystem Management and Restoration Research Program (EMRRP),3909 Halls Ferry Road,Vicksburg,MS,39180**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**17**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

(ER 1105-2-100 (USACE 2000)). The same metrics should be used during development of monitoring plans to help decision makers understand the degree to which the project is delivering expected results and to inform adaptive management decisions. Section 2039 of the Water Resources Development Act (WRDA) of 2007 (US Congress 2007) recommends that USACE ecosystem restoration feasibility studies identify success criteria. The law allows for up to 10 years of federally cost-shared monitoring in the event that success criteria are not met in less than 10 years. USACE Implementation Guidelines for Section 2039 of WRDA 2007 specify that each ecosystem restoration monitoring plan must include key project-specific parameters to be measured and describe how those parameters, or metrics, relate to achievement of desired project outcomes or implementation of contingency options identified in the project's adaptive management plan (CECW-PB (USACE 2009)). Beyond policy requirements, effective monitoring is an essential aspect of ecosystem restoration as it demonstrates progress and the degree to which objectives are being satisfied to leadership, stakeholders, and future project sponsors. It also increases the depth and breadth of understanding about the effectiveness of ecosystem restoration practices, contributes to expanding knowledge about ecosystems, and guides management decisions on the most effective, efficient, and economical courses of action (Thom and Wellman 1996, Grootjans et al. 2002; USACE 2009). Appropriate, clearly defined metrics are essential to successful ecosystem restoration planning and monitoring programs and must be identified, quantified, and evaluated to select the best plan, track changes, and characterize project success.

Metrics used in plan formulation can be quantified by modeling and analysis, or can be qualitative in nature, while metrics used to assess project implementation success must come from direct measurements and analysis. Given the complexity of ecological systems and restoration objectives, a multitude of potential metrics are available for use. With limited funding, it may only be possible to effectively measure, estimate, or otherwise use a few metrics, so it is critical to carefully select the metrics that can clearly show the system state, test hypotheses, and track changes in ecosystem quantity and quality in the project area. Developing an effective yet pragmatic metric set necessitates integrating social and economic considerations with rigorous scientific concepts of ecological structure and function, while effectively accounting for tradeoffs among measured outputs (Walters 1997, Kiker et al. 2005).

Many current methods for selecting and comparing metrics result in metric sets that fail to capture the information necessary to develop project objectives and to determine the degree to which management actions have influenced the system and met project objectives. The lack of a robust framework for selecting a set of restoration metrics may result in sub-optimal choices that are ad–hoc, mimic historical practices and regulations, or apply screening criteria inconsistently, leading to restoration planning that carries subjective bias or applies insufficient physical, chemical, and ecological principles based on outdated assumptions (Kondolf 1995, Kondolf and Micheli 1995, Allen et al. 2002, Nienhuis et al. 2002, Neimeijer and de Groot 2008).

This technical note is intended to guide restoration planners through the difficult process of selecting effective ecosystem restoration metric sets in the face of limited resources, varied project objectives and stakeholder priorities, and a multitude of potential metrics to choose from. The remainder of this technical note reviews methods for metrics selection, assessment, and application that may be used under a variety of circumstances.

REVIEW OF METRICS SELECTION METHODS: Metrics must be measurable and should have desired targets or outcomes that relate to project objectives. These targets, which are specified by predictive models, data mining, or by best professional judgment, are used to compare predicted project plan performance to actual performance. To address the challenge of selecting an informative and appropriate set of metrics for restoration projects, this section first reviews and assesses existing methods of identifying possible metrics. Once the initial set of potential project-specific metrics has been developed, it must be narrowed to the optimal metric set depending on resource constraints and stakeholder priorities. This section later presents two methods, screening and multi-criteria decision analysis (MCDA), for use in narrowing metrics and compiling the optimal metric set. Metric identification methods include the following:

Conceptual modeling. Conceptual models generally illustrate relationships among key ecological parameters, target species and performance indicators, and attempt to simulate ecosystem dynamics and describe how system inputs translate to outputs (Harrington and Feather 1996, Ogden et al. 2005). They provide a link between early planning and later evaluation, synthesize current knowledge, and can be used to identify appropriate monitoring metrics (Harrington and Feather 1996, Thom and Wellman 1996, USACE 2005, USACE Environmental Advisory Board (EAB) 2006, Fischenich 2008). Ecosystem models can also be expanded to system models including the relevant economic, social, political, and other factors affected by or influencing environmental restoration projects. Conceptual modeling is an iterative process that involves multiple revisions and expansions to create models of varying detail that describe the relationship between relevant (i.e. those influencing the project objectives) system components. There are numerous conceptual model types that differ in both framework and presentation formats. Common conceptual model types, described in further detail in Fischenich (2008), include stress-response models, state and transition models, and driver-stressor-endpoint models.

For USACE ecosystem restoration projects, once the need for a conceptual model to identify appropriate metrics is recognized, proponents and appropriate Planning Centers of Expertise (PCXs) may use the conceptual model to investigate potential desires or needs for planning models that might be used during a study to evaluate the impacts of planning alternatives. Planning models must be certified and approved for use in accordance with EC 1105-2-412. In addition, conceptual models that illustrate relationships between structures, functions, and metrics that may be used to quantify each have been observed to facilitate communication of such relationships.

Though a number of approaches exist, the general conceptual modeling process includes seven steps (adapted from Grant et al. (1997)):

1. Formulate model objectives (Why is the team creating the model? What do they hope to accomplish/get out of it?)
2. Determine the extent of the model (What are the bounds of the system? Does the model include natural processes only or natural processes and socio-political influences?)
3. Describe the boundary and other assumptions adopted to simplify characterization of the system, seeking to understand the conditions under which the assumptions might be proven false and how that might affect the validity of information gleaned from the model's application.
4. Identify system components affected by or influencing project objectives.

5. Categorize related components according to their specific roles in the system or the model and establish relationships between system components.
6. Represent the conceptual model using a flow chart or other diagram type.
7. Describe expected pattern of model component behavior; usually this means describing changes in model components over time in response to specific scenarios.
8. Review, revise, and expand the model.

Once the conceptual model has been created, it can be used to identify and form a comprehensive set of metrics. From that set, planners should seek metrics that measure the most important system components (those impacting the project objectives or ecosystem quality and quantity) identified in the conceptual model.

For example, in the USACE guide to planning aquatic ecosystem restoration monitoring programs (Thom and Wellman 1996), the authors suggest a conceptual-model-based approach to selecting metrics that links project objectives to performance parameters (metrics). The project team creates an ecosystem model that relates three system components: controlling factors (e.g. elevation, hydrology, substrate), structure (e.g. salt marsh), and functional components or resources (e.g. waterfowl, shorebirds, fish). The model is designed to elucidate key factors that control both the development and maintenance of system structure and attributes and functions related to project objectives. The team then chooses metrics that measure aspects of each of these components while aiming to develop a scientifically based, easy-to-measure metric set that provides useful data about the system.

The approach involves three steps (adapted from Thom and Wellman 1996):

1. Reduce the system into related controlling, structural, and functional components or resources relative to project objectives (i.e. create the conceptual model).
2. Identify measurable metrics within each component.
3. Compile a subset of metrics from the initial set that represents all model components, and measures environmental benefits of the project and progress toward project objectives. At least one component for each of the earth science “spheres’’ that can describe an ecosystem should be selected, including physical, hydrological, and ecological measures (National Resource Council (NRC) 1992).

Another example of a conceptual ecological model (CEM), recently developed for a feasibility-level monitoring and adaptive management plan, is based on a top-down hierarchy of information organized into drivers, stressors, effects, attributes, and performance measures. Members of an interagency project team created the model by reviewing existing information about the ecosystem, meeting to discuss reasons for natural and anthropogenically driven area alterations, and developing lists of stressors and consequent ecological effects (USACE 2010). To develop monitoring metrics, the team then identified attributes that could serve as key indicators of project success through assessment of related performance measures. They used their hypotheses and lists to create the initial CEM draft, which was then further revised (Figure 1).

Pros: The conceptual model method can provide decision makers with a clear view of important factors and their relationships, making it easier to develop and/or approve of a metric set that satisfies multiple appropriate lifecycle needs. These relationships reveal what should be considered

during planning, implementation, and monitoring activities, and therefore which attributes project metrics should aim to assess. A CEM is useful because it requires planners to contemplate connections between relevant system components, and helps to identify key project components to improve ecosystem structure and function (Thom and Wellman 1996, Gentile et al. 2001). USACE policy requires the use of models for all planning activities and USACE guidelines recommend conceptual modeling specifically for metrics selection (Thom and Wellman 1996, EC 1105-2-407 (USACE 2005)). The use of a CEM also provides stakeholders with accountability by illustrating how the chosen metrics fit into the system and address specific objectives. In addition, it can involve and incorporate knowledge and opinions from a variety of stakeholders and professionals. Early formulation of a conceptual model can serve other potential needs as well, such as those that might be associated with various agency/USACE-specific policies. For instance, early formulation of a CEM can provide a platform to initiate discussion of planning, review, and monitoring-related evaluation, modeling, and monitoring needs that can, in turn, reveal insights about the potential linked roles to be served by metrics. Depending on the state of knowledge in a particular system, costs and time can range from relatively low to moderate compared to other methods.

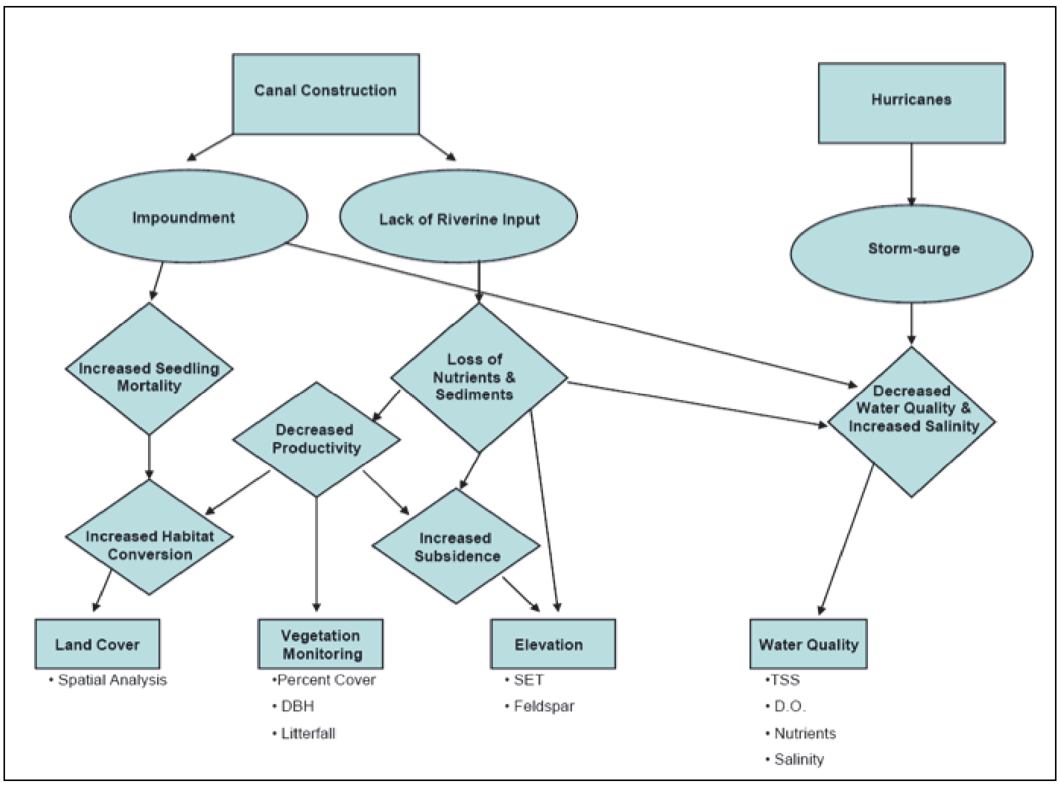

Figure 1. Example CEM created for a Louisiana Coastal Area ecosystem restoration monitoring and adaptive management plan designed to restore hydrologic connectivity and improve fish and wildlife habitat. Top rectangles represent drivers, ovals represent ecological effects, diamonds represent ecological stressors, and lower rectangles represent attributes. Bulleted items at the base of the diagram are performance measures or metrics that correspond to each attribute (from USACE (2010)).

Cons: The conceptual modeling approach to selecting metrics often does not assign weights or prioritize the model components. Therefore, this approach does not aid in making trade-offs

between metrics measuring the same or different components (USACE 2010). The conceptual modeling approach still leaves room for bias, as best professional judgment is often relied on to develop the model, though significant documentation and involvement of stakeholders or a wide variety of professionals can lessen this. Conceptual models are simplifications that usually focus only on the ecosystem components deemed most relevant while leaving out less important or less understood factors.

When to use conceptual models: Conceptual models required for project planning should always be consulted when selecting metrics. The approach is most useful when knowledge about the specific system and component relationships is available and well understood, and when the most important factors are known. Conceptual modeling can be used in a situation where there is little funding for monitoring and evaluation planning, and when planning needs to be done quickly if a suitable model already exists or the system is not overly complex. Metrics selection using this method should be supported by other methods to conduct trade-offs among potential metrics identified with the CEM.

Historical precedence. In the absence of more structured methods, historical precedence (i.e. historical practice) is often used to inform metrics selection. In this method, decision makers review metrics used in similar ecosystem restoration monitoring and evaluation programs, compile a list of these previous metrics, and assess and narrow them down based on specific project criteria and/or screening criteria (see "Screening" below). The approach can be simplified into three steps:

1. Conduct a literature search to identify metrics used to evaluate similar objectives in related projects. The literature search should cover projects that have occurred in the same or a similar region and/or ecosystem type, respond to similar disturbances, involve similar stakeholders, and have similar objectives and evaluation criteria.
2. Compare, evaluate, and refine the metric list using screening criteria (e.g., is the metric relevant to the ecosystem, does it provide useful information about the ecosystem state and specific project objectives, is the metric sensitive to changes in the system, how well did the metric measure success in previous projects?)
3. Compile a subset of appropriate metrics from the initial set based on region and system specifics, project objectives, and ecological concerns.

Pros: Maintaining use of historical metrics often allows for easy comparison to baseline data and cross-comparison among projects, particularly within a region or restoration program. Availability of similar, previously measured data makes it easier to set measurement goals, and allows managers to evaluate system conditions compared to not only baseline conditions but historical conditions as well. Often, metric measurement and evaluation methods are well established. The method can be low cost and time efficient.

Cons: Choosing metrics based on historical precedence is not always a transparent process (i.e., reasons for selecting the metrics are not always clear or clearly communicated), may hide individual bias (i.e. certain project-specific objectives may be implicitly over-emphasized or de-emphasized by the decision maker), is less rigorously justifiable than other methods, and may overlook differences in context. The method also may not successfully incorporate new stakeholder values or require decision makers to include new information and project specifics in the decision-making process. Using this method may encourage project planners to choose

previously used metrics that may not be most suited to their projects. Historical metrics should be used with caution, as multiple modifications may have caused significant changes to the needs and restoration goals of the system. Additionally, this method does not support development of new measurement techniques or technologies.

When to use historical precedence: This method should be used when restoration managers are able to review past projects that had very similar ecosystem characteristics and project goals, and in which practitioners were found to be capable of evaluating restoration needs and documenting the cause of observed impacts. Historical precedence should be considered when the previously used ecosystem restoration metrics address specifics of the current project, when the metrics have proven to be useful in the past, and when the use of metrics can be justified with respect to current project goals. The method may also be appropriate for low-budget and time-sensitive projects.

Best professional judgment (BPJ). In this method, project managers or larger technical advisory groups select metrics directly by integrating multiple lines of science-based and socioeconomic reasoning to form a conclusion, invoking a professional opinion that is case-specific (Linkov et al. 2009). Experts may be interviewed to identify potential ecosystem restoration metrics corresponding to decision criteria and project objectives based on their knowledge of the species or ecosystem process. Multiple project objectives, relative importance, and relation to ecosystem structure, function, and benefits, may all be integrated informally; however, significant documentation to justify conclusions and recommendations is usually required (Jones et al. 2002, Oliver 2002, Rohde et al. 2004, Choy et al. 2009). The same values that describe desired outcomes in the ecosystem may be used to identify success criteria for assessing actual project plan performance in the future. In other cases, the success criteria may relate to a comparison of progress towards the idealized project outcome with the current baseline and/or predictions of future trends.

Pros: BPJ is straightforward and generally inexpensive and time-efficient. It emphasizes, or sometimes solely involves, the judgment of individuals who are experienced and familiar with the specific case of ecological restoration.

Cons: Metrics selection via BPJ may exclude or place bias on specific stakeholder values or expert experience and is not an entirely transparent process (i.e. reasons for selecting the metrics are not always clear). It is challenging to correctly integrate a wide variety of influencing factors (including science-based ecological concepts and socioeconomic concerns) without structured methods, especially when dealing with complex systems. Without assistance, decision makers may have difficulty incorporating and evaluating the multitude of factors and relevant details associated with metric selection.

When to use BPJ: BPJ is often used to supplement other methods, but is also appropriate for restoration projects involving relatively homogeneous systems (e.g. a small wetland) and/or projects having few objectives. The method is also more appropriate for low-profile projects with few stakeholders and little public attention. In other scenarios, it may be necessary to use BPJ if the project is limited to a small budget and/or more rigorous methods are not feasible. It can also be used for complex projects once more structured methods have simplified the problem. Additionally, BPJ can be used to narrow options for metrics to an optimal list.

Narrowing the options: Screening. Restoration project managers can evaluate or "screen" potential metrics to identify the most appropriate subset of metrics for a given project (Table 1). Most screening criteria are applied to each potential metric individually. Each metric in the selected set should be relevant, unambiguous, direct, operational, analytically sound, measurable, responsive, and anticipatory to the greatest extent possible (McKay et al. 2012). The remaining criterion applies to the entire set—the metrics set should be comprehensive. Project managers can either use the criteria as a checklist, or rate each metric's potential on a scale for each of the criteria, if higher resolution is needed. Screening is often used to supplement other metric selection methods.

Table 1. Summary of screening criteria for metrics selection. Descriptions are adapted from the publications referenced within the table.

Screening Criteria	Description	EPA EMAP Evaluation Guidelines for Ecol. Indicators (Jackson et. al. 2000)	NRC Ecol. Indicators for the Nation (NRC 2000)	Keeney and Gregory (2005)	Societal Indicators for the National Climate Assessment Report (USGRP 2012)	International Council for Exploration of the Sea (ICES) (2001)	Dale and Beyeler (2001)
Operational	Information can be reasonably obtained.	√	√	√	√	√	√
Direct	Metrics directly describe the potential consequences of the project, especially what can be controlled by human actions.	√	√	√		√	√
Relevant	Metrics provide information about the project-specific objectives, at the correct spatio-temporal scale(s).	√	√			√	√
Unambiguous	Metrics clearly measure consequences of project alternatives.	√	√	√			√
Measurable	Data can be collected and are available over a large proportion of the area under consideration.	√	√		√	√	
Understandable	Metrics can be readily interpreted by technical team and communicated to audience.		√	√	√	√	
Analytically sound	Metrics are scientifically defensible and transparent in their presentation of methods and data.	√	√		√		
Comprehensive	Metric set addresses all project objectives and range of potential consequences.	√		√	√		√

Pros: Screening is another inexpensive and time-efficient process. Criteria are well-documented, and project managers can screen potential metrics efficiently without specialized programs. Screening criteria in Table 1 satisfactorily define the necessary qualities for each metric.

Cons: Screening does not facilitate formal consideration of individual metric utility within the total constellation of its metrics set (Niemeijer and de Groot 2008). Most of the criteria apply to individual metrics, and there is no internal method to determine whether the set of metrics is comprehensive. Additionally, there is no explicit consideration of project-specific stakeholder values though these may be incorporated using additional criteria.

When to use it: Screening is a valuable step in metrics selection for all ecosystem restoration projects, if one or more of the evaluation criteria presented in Table 1 have not been considered in other ways. For example, since MCDA may not consider whether the potential metrics are operational or measurable, restoration planners can use screening based on these two criteria in conjunction with MCDA.

Narrowing the Options: Multi-criteria decision analysis (MCDA)

MCDA modeling is a structured approach to decision making that quantitatively evaluates project choices (in this case, metrics) based on defined criteria, estimated value, and stakeholder preferences. MCDA integrates a wide variety of information to evaluate and rank potential metrics based on their ability to fulfill designated monitoring plan criteria (e.g. measuring progress and fulfillment of specific project objectives, informing adaptive management planning, etc.). By providing decision makers with the relative utility of each potential metric (both overall and with respect to individual monitoring plan criteria), MCDA analysis allows them to conduct trade-offs among the various choices and select the optimal set.

Selection of a project-specific set of metrics is tailored, case by case, from a general set of metrics according to the stakeholders' preferences and the set of criteria/subcriteria. As a tool for metric selection, a Multi-Criteria Decision Analysis is performed according to the following steps:

1. Establish a set of metric choices to be assessed and ranked. These can be created specifically for the project at hand using one of the above methods or come from an existing list of metrics (e.g. Thayer et al. 2005). See McKay et al. (2012), also from the EMRRP technical notes collection, for more metric development guidance.
2. Formulate comprehensive criteria and subcriteria that represent the goals of the monitoring plan including intended benefits and important aspects of the restoration project objectives.
3. Elicit preferences from managers, planners, and/or stakeholders to establish the relative importance of the criteria and subcriteria and assign each a corresponding weight.
4. Assign each metric a value score based on expert assessment of the metric's ability to provide useful information about each of the criteria and subcriteria.
5. Input criteria, subcriteria, weights, and value scores into the MCDA model. (Other inputs such as uncertainty may also be required, depending on the MCDA method used. See the input section below for a more detailed description of each input.)
6. Calculate the weighted utility score and ranking of each potential metric that represents its contribution to the overall goal of the monitoring plan.

A general example of an MCDA model for metric selection (Figure 2) includes four main sections: overall goal, criteria, subcriteria, and alternatives (metrics).

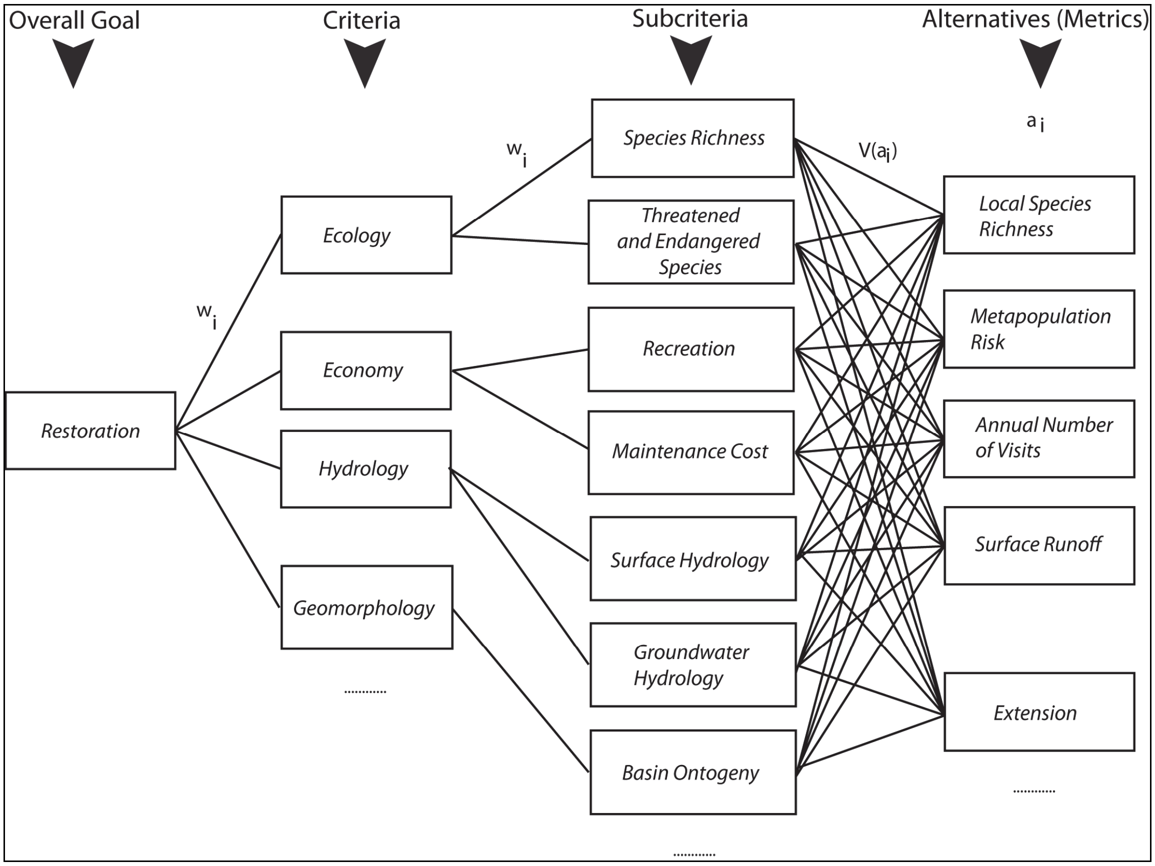

Figure 2. MCDA decision tree showing example overall objective, criteria, subcriteria, and metric alternatives for a sample aquatic restoration project and how they are related and structured within MCDA framework. Here the overall goal is restoration, with four main project criteria, or objective categories, including ecology, economy, hydrology, and geomorphology. Main criteria then have subcriteria that describe more specific categories of objectives (e.g. hydrology is split into surface and groundwater hydrology), so that each of these objective categories may be weighted and scored separately. The right side of the model shows the metric choices that the model will evaluate with respect to the criteria. In the tree, w_i represents the assigned weights of the criteria and subcriteria and $V(a_i)$ represents the value score of each metric with respect to each criterion and subcriterion. The utility, and therefore the ranking of each metric, a_i, is a function of the ability of each metric to describe the criteria and subcriteria (value score) and the relative importance of describing those criteria and subcritera (weights).

The user inputs:

1. Various potential project metrics based on established lists or specified by the project team and/or stakeholders.
2. Criteria based on broad project objective categories defined by the project team, technical advisory team, and/or stakeholders.
3. Subcriteria based on specific project objectives within the main criteria and defined by the project team, technical advisory team, and/or stakeholders.

4. Weights for the criteria and subcriteria that represent the importance of fulfilling each criterion and subcriterion relative to the others based on project team, technical advisory team, and/or stakeholder preferences.
5. Value scores that represent each metric's ability to provide information about each criterion and subcriterion based on expert evaluation.

Once users have input this information (and additional data specific to the MCDA method) into an MCDA software program and run the model, the program will rank each metric based on its contribution to the overall goal. Model inputs can easily be adjusted to determine the effect of varying preferences and, with certain MCDA methods, varying uncertainty. Uncertainty is considered in some MCDA methods by requiring the modeler to input a range of possible values and a measure of the certainty of those input values. Instead of producing a single rank for each metric, it calculates the probability that each metric will have each rank. Incorporating uncertainty into the understanding of the metrics can help identify project alternative plans that are more robust (i.e., capable of performing over a wide variety of uncertain future conditions) and/or flexible (i.e., able to adjust in the adaptive management context to improve probability of achieving ecosystem restoration goals and objectives). Metrics that are more uncertain may justify the need for a more robust design and/or inclusion of contingency options in the project adaptive management plan. For more information and several examples of MCDA modeling, see Linkov and Moberg (2011).

Pros: MCDA can be comprehensive and inclusive, incorporating modeling results and expert opinion on a variety of subjects as well as stakeholder preferences from several fields. The method allows planners to simplify complex situations with varied and often conflicting options, objectives, and opinions. New and changing information can easily be integrated and assessed. Decision makers can clearly justify management choices according to model results and interested parties can easily review components of the model including weights and alternative scores. The MCDA method thus enables restoration project managers to make systematic and transparent decisions (Reichert et al. 2007). It encourages input from multiple stakeholders and allows decision makers to evaluate the effect of varying preferences, thereby lowering likelihood of biased results. The quantitative results allow decision makers to clearly and easily compare each metric choice. MCDA standardizes and simplifies complex decision making, resulting in transparent, robust, efficient, and accountable restoration planning.

Cons: MCDA is highly dependent on the comprehensiveness of the criteria, the involvement of stakeholders, and the experts' ability to accurately quantify each metric's value to each criteria. The project team must be careful to choose a variety of stakeholders to avoid bias, and must consult knowledgeable experts to provide the value scores. Done well, MCDA can be time-consuming and can be more expensive than other methods. Conversely, when done poorly, it can complicate communication, and obfuscate the planning team's rationale for selecting and prioritizing metrics. Also, stakeholder opinions may conflict and each stakeholder's contribution to the assigned weights must be established. Additionally, the method is designed to narrow down chosen metric alternatives, not choose them explicitly, and does not include guidance for choosing the original larger metric set.

When to use MCDA: This method should be used when many diverse stakeholders are interested in the project, the situation is complex (several objectives and metric options being considered), and several months are available for conducting the MCDA. It can be useful when the situation involves multiple, varied, or conflicting objectives and competing stakeholder interests. It is also useful with projects involving adaptive management, as the model can easily be updated and the system reevaluated. Restoration managers may find it useful to use screening before or after MCDA to generate an initial list of metrics from a comprehensive set.

CHOOSING A METRICS SELECTION METHOD: Metrics selection requires careful consideration of a multitude of factors, but above all, individual metrics must evaluate specific project objectives and the chosen set must accurately assess overall project success according to all relevant criteria. Choosing metric selection methods depends on a number of factors, including:

- project scope
- degree of complexity (e.g. number of objectives and criteria)
- expert knowledge and availability
- project team knowledge
- stakeholder involvement and interest
- available historic data and similar project examples
- budget and time constraints
- intended use of information gathered from the metrics

Investment in metric selection, in terms of time, money, collaboration, and understanding of the system will likely correlate with the benefits gained from monitoring and evaluation. A more appropriate, robust metric selection method will typically lead to greater project transparency, defensibility, and utility. In general, a variety of metric selection methods may be employed simultaneously or consecutively to reach the optimal metric set. Additional techniques for metric comparison and combination can be found in McKay et al. (2012).

APPLYING METRICS TO RESTORATION EVALUATION AND MONITORING: Metrics are used to inform planning and track progress toward restoration goals throughout a project's lifecycle. During the project planning phase, metrics are used to screen management measures, and evaluate, compare, and select alternative plans (Engineer Regulation 1105-2-100 (2-3) (USACE 2000)). As such, it is important to consider the scalability of metrics that might be applied during different phases of a project's lifecycle (from planning through adaptive management of a constructed project). Metrics applied during different phases should be selected to be compatible and complementary with one another, but scaled to the level of detail, accuracy, and precision required to answer specific information needs of the study/project phase. Quantitative metrics used to develop evaluation parameters such as habitat units are combined with qualitative metrics to describe the benefits of the project alternative plan. In addition, some metrics may be in the form of measured constraints on project alternatives (i.e., water quality, endangered species, water supply, etc.) and are also incorporated into the recommended plan selection process.

Once a plan is selected, the metrics used to evaluate potential performance should also be used to assess actual success following project implementation. If uncertainty is associated with the achievement of the project objectives, then the monitoring parameters and corresponding success criteria should include additional metrics related to resolving uncertainties and specific triggers

or thresholds for making adjustments to improve performance based on the project adaptive management plan. Ecological thresholds are often characterized as a point, range, or distribution beyond which an important change occurs in an ecosystem condition, such as a state, pattern, or process (Bennetts et al. 2007). The subsequent trigger for adaptive management action should ideally be related to the time required for the metric to have responded to the restoration action based on values of the monitoring data and/or expected recovery time from the literature.

Information gathered from the chosen set of monitoring metrics will also be used to determine the ultimate effectiveness of restoration actions and the degree of overall project success. This success is based on the state of the chosen restoration metrics with respect to success criteria that have been clearly and precisely defined during pre-construction planning (CECW-PB (USACE 2009)). This must be proved using the pre- and post-project implementation values of the monitoring metrics.

Actual project results are compared with the predicted outcomes of restoration activities to indicate the degree of project success. First, before any project construction or ecosystem modification, the team must establish baseline values of the chosen metrics under pre-construction conditions. Often, existing data can be used to establish this baseline. Using these baseline values, professional judgment, modeling and/or literature review, the team predicts or sets targets for post-construction values for the chosen metrics based on the predicted or desired effects of their restoration actions. Once post-construction monitoring has commenced, predicted and realized metric values are compared to measure success.

When a more structured, quantitative method of evaluating project success is necessary, such as in a more complex project, a useful method of determining success is conducting a weight of evidence (WOE) evaluation. In this method, threshold metric values are established that might be project-specific or categorical across all projects, depending on the metric. Each project objective is then evaluated as “successful/unsuccessful” (binary) or on a numerical scale for each metric. The evaluation based on each metric thus generates a line of evidence about project success at achieving stated objectives, and can be used to document and prove success, or advise adaptive management actions, future project implementation, or restoration program priorities (Linkov et al. 2009).

Planners have access to a range of qualitative and quantitative tools to integrate multiple lines of evidence into a cohesive evaluation of project success. Choice of method for WOE depends on the purpose of the evaluation (communication, adaptive management, funding, informing future projects, etc.). Ordered from qualitative (or least quantitative) to most quantitative, the available methods for weight of evidence evaluation include: listing evidence, best professional judgment, indexing, and quantitative evaluation (e.g. MCDA) (Linkov et al. 2009).

Listing evidence is the simplest application of WOE, as it does not integrate the multiple lines of evidence (Linkov et al. 2009). If an assessment of overall restoration success is not necessary, listing evidence may be appropriate for communication to specific stakeholders concerned about individual objectives, informing future project management, or guiding adaptive management. Other WOE methods attempt to integrate the lines of evidence to form a conclusion (Linkov et al. 2009). Best professional judgment is defined as qualitative integration of multiple lines of evidence, and is generally case-specific. Indexing is defined as integration of lines of evidence into

a single measure based on empirical models. Quantification is defined as integrated assessment using formal decision analysis and statistical methods, and includes MCDA (Linkov et al. 2009). Quantification is the most transparent and therefore often most useful method for consensus building. Specifically, it allows scientific lines of evidence (here, information gathered from metric assessment) and social, political, logistical, economic, or other considerations to be integrated explicitly and systematically (Linkov et al. 2009). Quantification, especially MCDA, may be most appropriate where the project evaluation based on multiple metrics must be used in further decision making such as adaptive management or informing future projects, or where transparency is important for communication to stakeholders. Structured and quantitative approaches to WOE are preferred where possible (Weed 2005, McDonald et al. 2007, Linkov et al. 2009).

CONCLUSION: This technical note assists ecosystem restoration project planners in selecting the best metrics to identify the recommended plan, resolve uncertainties, and monitor and evaluate progress toward project objectives. Choosing metrics that effectively measure project objectives, such as specific environmental benefits, is critical to effectively plan, monitor, and evaluate ecological restoration projects and make informed decisions to improve project performance. Project managers and physical scientists often lack a robust framework for identifying, developing, and selecting metrics. This technical note discussed the importance and difficulty of choosing appropriate metrics, and reviewed metric selection methods including conceptual modeling, historical precedence, best professional judgment, screening, and multi-criteria decision analysis. A number of factors determine the best metric selection method(s) for each project, including: specific project scope, expert knowledge and availability, project team knowledge, stakeholder involvement and interest, available historic data and similar project examples, budget and time constraints, and the intended use of information gathered from the metrics. This document highlights the strengths and weaknesses of each method and suggests the best conditions for use. Finally, WOE methods were examined as a way to evaluate restoration objectives based on the metric data. Thoughtful and deliberate metrics selection and utilization will most often lead to increased project benefit through well-informed planning and adaptive management, greater monitoring and evaluation program efficiency, and additional scientific and operational knowledge.

ADDITIONAL INFORMATION: Research presented in this technical note was developed under the Environmental Benefits Analysis (EBA) Research Program. The USACE Proponent for the EBA Program is Rennie Sherman and the Technical Director is Dr. Al Cofrancesco.

Technical reviews were provided by Shawn Komlos, and John Wright.

For additional information, contact the corresponding author, Dr. Igor Linkov (617-233-9869, Igor.Linkov@usace.army.mil), or the manager of the Environmental Benefits Analysis Research Program, Mr. Glenn Rhett (601-634-3717, Glenn.G.Rhett@usace.army.mil). This technical note should be cited as follows:

> Convertino, M., K.M. Baker, C. Lu, J.T. Vogel, K. McKay, and I. Linkov. 2013. *Metric selection for ecosystem restoration*. EBA Technical Notes Collection. ERDC TN-EMRRP-EBA-19. Vicksburg, MS: US Army Engineer Research and Development Center. http://cw-environment.usace.army.mil/eba/

REFERENCES

Allen, C. D., M. Savage, D. A. Falk, K. F. Suckling, T. W. Swetnam, T. Schulke, P. B. Stacey, P. Morgan, M. Hoffman, and J.T. Klingel. 2002. Ecological restoration of southwestern Ponderosa pine ecosystems: A broad perspective. *Ecological Applications* 12(5): 1418-1433.

Bennetts, R.E., J.E. Gross, K. Cahill, C. McIntyre, B.B. Bingham, A. Hubbard, L. Cameron, and S.L. Carter. 2007. Linking monitoring to management and planning: Assessment points as a generalized approach. *George Wright Forum* 24(2): 59-77. http://www.greateryellowstonescience.org/files/pdf/Bennetts_et_al_GWF_Paper.pdf

Choy, S. L., R. O'Learey, and K. Mengersen. 2009. Eliciatation by design in ecology: Using expert opinion to inform priors for Bayesian statistical models. *Ecology* 90(1): 265-277.

Dale, V.H., and S.C. Beyeler. 2001. Challenges in the development and use of ecological indicators. *Ecological Indicators* 1: 3-10.

Fischenich, C. 2008. *The application of conceptual models to ecosystem restoration*. EBA Technical Notes Collection. ERDC TN-EMRRP-EBA-01. Vicksburg, MS: U.S. Army Engineer Research and Development Center. www.wes.army.mil/el/emrrp.

Gentile, J.H., M.A. Harwell, W. Cropper Jr., C.C. Harwell, D. DeAngelis, S. Davis, J.C. Ogden, and D. Lirman. 2001. Ecological conceptual models: A framework and case study on ecosystem management for South Florida sustainability. *The Science of the Total Environment* 274: 231-253.

Grant, W., E. Pederson, and S. Marin. 1997. *Ecology and natural resource management: Systems analysis and simulation*. New York: John Wiley & Sons, Inc.

Grootjans, A. P., H. W. T. Geelen, A. J. M. Jansen, and E.J. Lammerts. 2002. Restoration of coastal dune slacks in the Netherlands. *Hydrobiologia* 478: 181-203.

Harrington, K.W., and T. D. Feather. 1996. *Evaluation of environmental investments procedures overview manual.* Alexandria, VA: U.S. Army Corps of Engineers Institute for Water Resources.

International Council for Exploration of the Sea (ICES). 2001. *Report of the Working Group on Ecosystem Effects of Fishing Activities*. ICES Document, CM 2001/ACE: 09.

Jackson, L.E., J.C. Kurtz, and W.S. Fisher, eds. 2000. *Evaluation guidelines for ecological indicators.* EPA/620/R-99/005. Research Triangle Park, NC: US Environmental Protection Agency, Office of Research and Development.

Jones, G., T. Hillman, R. Kingsford, T. McMahon, K. Walker, A. Arthington, J. Whittington, S. Cartwright. 2002. *Independent Report of the Expert Reference Panel on Environmental Flows and Water Quality Requirements for the River Murray System*. Canberra, AUS: Cooperative Research Centre for Freshwater Ecology.

Keeney, R. L., and R. S. Gregory. 2005. Selecting attributes to measure the achievement of objectives. *Operations Research* 53(1):1-11.

Kiker, G .A., T. S. Bridges, A. Varghese, T. P. Seager, and I. Linkov. 2005. Application of multicriteria decision analysis in environmental decision making. *Integrated Environmental Assessment and Management* 1(2): 95-108.

Kondolf, G. M. 1995. Five elements for effective evaluation of stream restoration. *Restoration Ecology* 3(2): 133-136.

Kondolf, G. M., and E. R. Micheli. 1995. Evaluating stream restoration projects. *Environmental Management* 19(1): 1-15.

Linkov, I., D. Loney, S. Cormier, K. F. Satterstrom, and T. Bridges. 2009. Weight-of-evidence evaluation in environmental assessment: Review of qualitative and quantitative approaches. *Science of the Total Environment* 407: 5199-5205.

Linkov, I., and E. Moberg. 2011. *Multi-criteria Decision Analysis: Environmental applications and case studies.* Boca Raton, FL: CRC Press.

McDonald, B. G., A. M. H. DeBruyn, B. G. Wernick, L. Patterson, N. Pellerin, and P. M. Chapman. 2007. Design and application of a transparent and scalable weight-of-evidence framework: An example from Wabamun Lake, Alberta, Canada. *Integrated Environmental Assessment and Management* 3: 476–83.

McKay, S. K., I. Linkov, J. C. Fischenich, S. J. Miller, and L. J. Valverde, Jr. 2012. *Ecosystem restoration objectives and metrics.* EMRRP Technical Notes Collection. ERDC TN-EMRRP-EBA-16. Vicksburg, MS: US Army Engineer Research and Development Center.

Miner, S. P. 2005. *Operation, Maintenance, repair, replacement and rehabilitation manuals and inspections of completed projects for ecosystem restoration: An assessment of guidance needs*. Alexandria, VA: U.S. Army Corps of Engineers Institute for Water Resources.

Niemeijer, D., and R.S. de Groot. 2008. A conceptual framework for selecting environmental indicator sets. *Ecological Indicators* 8:14-25.

Nienhuis, P. H., J. E. Bakker, A. P. Grootjans, R. D. Gulati, and V. N. De Jonge. 2002. The state of the art of aquatic semi-aquatic ecological restoration projects in the Netherlands. *Hydrobiologia* 478: 219-233.

National Research Council (NRC). 1992. *Restoration of aquatic ecosystems.* Washington, DC: National Academy Press.

National Research Council (NRC). 2000. *Ecological indicators for the nation* Washington, DC: National Academy Press.

Ogden, J., S. Davis, K. Jacobs, T. Barnes, and H. Fling. 2005. The use of conceptual ecological models to guide ecosystem restoration in south Florida. *Wetlands* 25(4): 795-809. http://www.bioone.org/doi/pdf/10.1672/0277-5212%282005%29025%5B0795%3ATUOCEM%5D2.0.CO%3B2

Oliver, I. 2002. An expert panel-based approach to the assessment of vegetation condition within the context of biodiversity conservation; Stage 1: The identification of condition indicators. *Ecological Indicators* 2: 223-237.

Reichert, P., M. Borsuk, M. Hostmann, S. Schweizer, C. Sporri, K. Tockner, and B. Truffer. 2007. Concepts of decision support for river rehabilitation. *Environmental Modeling and Software* 22: 188-201.

Rohde, S., F. Kienast, and M. Bürgi. 2004. Assessing the restoration success of river widenings: A landscape approach. *Environmental Management* 34: 574–589.

Thayer, G.W., T.A. McTigue, R.J. Salz, D.H. Merkey, F.M. Burrows, and P.F. Gayaldo, (eds.). 2005. *Science-based restoration monitoring of coastal habitats, Volume Two: Tools for monitoring coastal habitats.* NOAA Coastal Ocean Program Decision Analysis Series No. 23. Silver Spring, MD: NOAA National Centers for Coastal Ocean Science.

Thom, R. M., and K. F. Wellman. 1996. *Planning aquatic ecosystem restoration monitoring programs*. IWR Report 96-R-23. Pacific Northwest National Laboratory, Richland, WA; final report prepared for U.S. Army Corps of Engineers Institute for Water Resources, Alexandria, VA.

US Army Corps of Engineers (USACE). 2000. *Planning Guidance Notebook*. ER 1105-2-100. Washington, DC.

US Army Corps of Engineers (USACE). 2005. *Planning Models Improvement Program: Model Certification*. EC 1105-2-407.

US Army Corps of Engineers (USACE), Environmental Advisory Board (EAB). 2006. *Environmental benefits and performance measures: Defining national ecosystem restoration and how to measure its achievement.* Report to the Chief of Engineers. December 2006.

US Army Corps of Engineers (USACE). 2009. *Implementation Guidance for Section 2039 Monitoring Ecosystem Restoration*. CECW-PB Memorandum.

US Army Corps of Engineers (USACE). 2010. *Louisiana Coastal Area (LCA) Program: Amite River Diversion Canal Modification Project Feasibility-Level Monitoring and Adaptive Management Plan*. New Orleans, LA: US Army Engineer District, New Orleans.

US Congress. 2007. H.R. 1495--110th Congress: Water Resources Development Act of 2007 (WRDA). In *GovTrack.us (database of federal legislation).* Retrieved October 14, 2011, from http://www.govtrack.us/congress/bill.xpd?bill=h110-1495

US Global Change Research Program (USGCRP). 2012. *Climate change impacts and responses: Societal indicators for the national climate assessment.* The United States National Climate Assessment, NCA Report Series, Vol 5c. USGCRP NCA Workshop Report.

Walters, C. 1997. Challenges in adaptive management of riparian and coastal ecosystems. *Conservation Ecology*[online]1(2):1. Available from the Internet. URL: http://www.consecol.org/vol1/iss2/art1/. Accessed 30 January 2013.

Weed, D.L. 2005. Weight of evidence: a review of concept and method. *Risk Analysis* 25: 1545–57.